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REPORT OF INVESTIGATIONS/1989

Leakage Across a Bituminous Coal Mine Barrier

By Noel N. Moebs and Gary P. Sames

BUREAU OF MINES

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	in	inch
gal	gallon	mD	millidarcy
gpm	gallon per minute	psi	pound per square inch
hp	horsepower	V ac	volt, alternating current

LEAKAGE ACROSS A BITUMINOUS COAL MINE BARRIER

By Noel N. Moebs[1] and Gary P. Sames[2]

ABSTRACT

The U.S. Bureau of Mines is conducting research on many topics relating to the hazards of coal mining, increased production, and protection of the environment. One area of research that has received scant attention in recent years is that of water inflows, probably because few fatalities in the United States have been attributed to them. As mining goes deeper, the problem of water inflow could increase dramatically because of adjacent or overlying mines in which huge water pools are impounded. Inaccurate mine maps and ineffective barriers can constitute a serious problem for operators both from gradual inflows and sudden inrushes of water. This report describes a wide but ineffective barrier that permitted an average 240-gpm inflow to a developing mine from an adjacent mine. The anomalous geologic structure that facilitated this leakage is described, demonstrating that size, alone, is no assurance against serious leakage. Some recommendations for managing serious water inflow are included.

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INTRODUCTION

The adequacy of coal barriers as a protection against inundation from nearby flooded mines is becoming more critical as mining in the United States goes to greater depths. Failure to properly assess the geohydrologic parameters can result in excessive pumping and treatment costs or, in the worst scenario, a sudden inrush of water.

Inundations of active coal mine workings from flooded adjacent or superjacent workings have plagued operators for decades. Sudden inrushes are by far the most dangerous, accounting for numerous fatalities over the last two centuries. Table 1 shows some of the major inundation disasters of this period that occurred in England and Scotland, where there has been a very long history of coal mining. Reporting of mine inundations is incomplete for the earlier years as only major disasters were recorded. No doubt the toll in lives was greater than indicated. While a few of these disasters resulted from shallow workings unexpectedly driving into saturated soil or peat, the majority occurred when unchartered mine workings were intercepted.

In the Chasnala, India, disaster of 1975 (*1*),[3] 372 miners died when a coal barrier impounding some 110 million gallons of water under a hydraulic head of 320 ft was inadvertently penetrated. In 1975, 45 miners were drowned in an inundation disaster in northern Taiwan and in 1984, 10 miners died in a similar accident in Hebei Province, China (*2*).

A somewhat unusual inundation disaster occurred at the Yung-Ann Mine, Shih-Chiao-Ting, Juifang Township, Taiwan, on March 21, 1980, when active mining crossed a structural fault that formed the boundary of an adjacent flooded mine (*3*). The problem was compounded by the Keelung River overlying the adjacent mine, as openings in the river bed connected directly with the adjacent mine and added to the difficulty of the recovery operation. The inundation was very rapid and without warning, resulting in 34 fatalities.

Sheard and Hurst (*4*) described an instance in which no leakage was reported, although test holes had tapped some water, and water suddenly broke through a barrier only 2 ft wide drowning two miners. The water head was 60 ft, equal to 26 psi. This suggests that seepage through and over a coal barrier is not always present in quantities sufficient to warn of imminent failure. Thus, inundation accidents have continued to occur occasionally into recent decades despite improved safety measures and engineering control.

Sudden inrushes of water have been somewhat less of a problem in the United States than in England and Scotland partly because the era of large-scale coal mining has been shorter and more drift than shaft mining has been practiced in the United States. Nonetheless, table 2 shows some of the recorded inundation fatalities of a century or so of mining. Of these inundations, about half occurred as a result of very shallow mining that broke into saturated sand, gravel, or clay deposits, while the remainder resulted from inadvertent penetration of a coal barrier.

Figure 1 shows the distribution of recorded inundation fatalities in the U.S. from 1883 to the present, and while nonfatal inundation accidents have been reported in detail only since 1975 (fig. 1), an accident often is but a little short of becoming a fatality. This suggests that a potential for additional inundation fatalities remains high.

As mining in the United States becomes progressively deeper, the probability of mining either beneath, alongside, or downdip from flooded workings also increases, along with the need to reliably assess barrier thickness and integrity. Failure to design adequate future barriers, or to fully assess the adequacy of existing barriers through geotechnical methodology, could lead to overwhelming problems with mine water in the years ahead.

[3]Italic numbers in parentheses refer to items in the list of references at the end of this report.

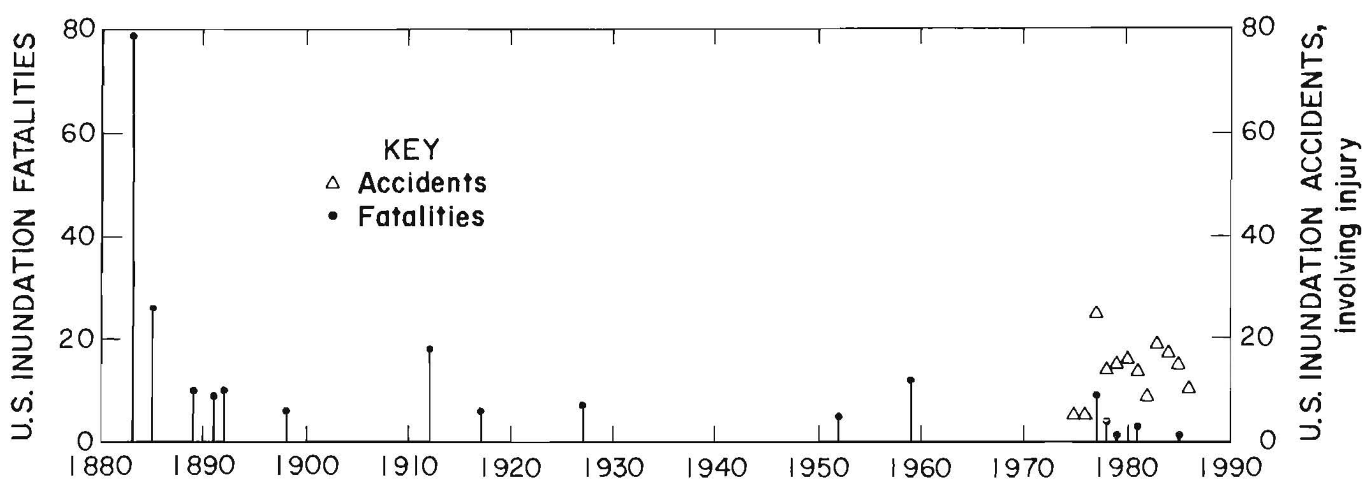

Figure 1.–Inundation accidents and fatalities in the United States, 1883-1987.

Table 1.–Selected inundation accidents in England and Scotland

Year	Mine	Fatalities
1815	Heaton Colliery, Northumberland, England	90
1837	Workington Colliery, West Cumberland, England	27
1895	Audley Colliery, North Staffordshire, England	77
1901	Donibristle, Scotland	8
1908	Roachburn, Scotland	3
1918	Stanrigg-Arbuckle, Lanarkshire, Scotland	19
1923	Redding Colliery, Falkirk, Stirlingshire, Scotland	40
1925	Montagu Colliery, Northumberland, England	38
1950	Knockshinnoch Colliery, Ayrshire, Scotland	13
1973	Lofthouse Colliery, Northumberland, England	7

Source: Duckham H., and B. Duckman. Great Pit Disasters. Divad and Charles Publ., North Pumfret, VT, 1973, 227 pp.

Table 2.–Selected inundation accidents in the United States

Year	Mine and location	Fatalities
1883	Diamond Mine, Braidwood, IL	69
1885	No. 1 Slope, Nanticoke, PA[1]	26
1889	White Ash Mine, Golden, CO	10
1891	Spring Mountain Mine, Jeansville, PA[1]	9
1892	Lytle Mine, Minersville, PA[1]	10
1898	Williams Mine, Middleport, PA[1]	6
1912	Superba-Lemont Mines, Evans Station, PA	18
1917	Wilkeson Mine, Wilkeson, WA	6
1927	Carbonado Mine, Carbonado, CO	7
1952	Holmes Slope, Forrestville, PA[1]	5
1959	River Slope, Port Griffith, PA[1]	12
1977	Porter Tunnel Mine, Tower City, PA[1]	9
1978	Moss No. 3, Dante, VA	4
1979	Mine No. 1, Poteau, OK	1
1981	Harlan No. 5 Mine, Grays Knob, KY	3
1985	Lykens No. 6 Mine, Lykens, PA[1]	1

[1]Anthracite mine.

Sources: Keenan, C. M. Historical Documentation of Major Coal-Mine Disasters in the United States Not Classified as Explosions of Gas or Dust: 1846-1962. BuMines Bull. 616, 1963, 91 pp. (1883-1959 data), and Health and Safety Analysis Center accident file (from the Mine Information Systems of the Denver Safety and Health Technology Center of the Mine Safety and Health Administration (1977-85 data).

The hazards of a sudden inrush of water, while of the utmost concern to mine operators and enforcement personnel, should not entirely overshadow the importance of providing for coal barriers that not only will withstand a sudden failure and inrush but will also prevent significant leakage. Leakage may lead to dissolution and piping of the coal and surrounding rock, and to prolonged pumping and water treatment. Peters (*5*), in discussing the coal mine drainage problems of North Derbyshire, mentions that even small flows are an important "nuisance" factor because of their effect on very high cost machinery.

As succinctly expressed by Berry (*6*), "The handling and disposal of mine water is a much larger problem than is apparent at first glance." Water must be removed from active mines to prevent a buildup that eventually fills low places, blocks traffic and ventilation, and interferes with the mining cycle, especially in low coal. In addition, water can cause severe deterioration of mine roof consisting of clay shale or claystone and may prevent the proper installation of resin-anchored bolts if the water seeps through the roof in large quantities. Mine water that does not meet State or Federal water quality standards will require treatment, which entails sludge disposal, before being released into surface streams. Thus, mine water can contribute to an array of problems, all adding to the cost of mining coal.

Although the quantity of water that must be pumped from active U.S. bituminous coal mines varies widely it has been estimated to be in the range of 5 to 6 tons of water for each tone of coal produced (*6*). This range would include water from pillared sections of shallow mines (less than 400 ft of cover), which tends to be seasonal but constitutes the major inflow in most large mines.

In comparison, Gazizov (*7*) reviewed the various types of mine water problems associated with the coal industry in the U.S.S.R. and reported that an average of 3.3 tons of water was pumped per ton of coal produced, about half the value for the U.S. mines. In addition, he notes that out of 2,600 coal faces inspected in 1979, only 4% to 5% were troubled by heavy water inflow, which is defined as one of 66 gpm or greater. Some 82% have only very small inflows, probably because of the large number of dewatering boreholes used to drain unconsolidated overburden and aquifers.

In contrast, mines in the anthracite region of eastern Pennsylvania pumped 36 tons of water per ton of coal (*6*), although some earlier estimates have been as high as 46.7 tons (*8*). These high values can be explained by the interconnection of many of the anthracite mines, numerous underground water pools, and the close proximity of the surface or buried river valleys. Mine water problems in the anthracite region can be largely attributed to the failure to leave adequate outcrop or interior barriers that would effectively have compartmentalized the mines.

Based on extensive experience with coal mine drainage problems, Peters (*5*) concludes that there is no easy or obvious solution to water drainage problems and stresses that no great reliance should be placed on barriers between old mine workings. In a similar vein, Davies and Baird (*9*) stress the difficulty in obtaining a single answer that will explain or cover all situations in which accumulations of water may be a threat. Despite these limitations in dealing with water problems it is imperative to conduct continuing geotechnical investigations of a broad scope in order to minimize mine water problems that already have plagued other countries and could become commonplace in the United States.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to T and T Coals, Inc., for providing assistance in test procedures and for unlimited access to their mine. Also, the authors wish to thank The Rochester & Pittsburgh Coal Co. and the Pennsylvania Bureau of Bituminous Deep Mine Safety for their helpful advice and information.

BARRIER WIDTH

LEGISLATION

Clearly defined limits for geometry and width of safety barriers are very seldom specified, and when they are, rules of thumb rather than scientific designs govern the barrier limits. Many parameters must be ascertained in order to determine these limits. Barrier pillar legislation has, in the past, been limited to property boundary barriers for approaching an abandoned mine. Although no State has a clearly defined method for computing an adequate barrier, they have other requirements that provide the States with authority to approve or disapprove a mining company's plans and thereby control barrier design.

West Virginia mining laws (*10*) do not address the subject of barriers except with respect to property boundaries and adjacent mines. Drilling of boreholes 20 ft in advance of the face is required when any working place approaches within 200 ft of any abandoned workings that cannot be inspected. This requirement closely follows the mandate of Federal regulations for mining near an abandoned mine, as discussed in "Recommendations" section, item 6. Mine operators, with approval of the State Mine Inspection Division, generally adopt a 100-ft-wide safety barrier to avoid shallow overburden, weathering, and fractures.

Two Federal agencies, the Mine Safety and Health Administration and the Office of Surface Mining, Reclamation and Enforcement, are responsible for enforcing regulations regarding mining. However, neither agency prescribes limits or design criteria for safety barrier widths. Each mining situation is evaluated independently to allow for local conditions.

Thus, there are no stringent design criteria for safety barriers, the width being largely determined by local subsurface conditions. The option of increasing the barrier width, for example, from 100 to 200 ft, to increase the safety factor must be weighed against the resulting loss of recoverable coal.

ENGINEERING FACTORS

Safety barriers are planned to provide entry stability, protection from water inflow, and as an air seal for ventilation purposes. Factors that are taken into consideration when deciding barrier width include previous roof control experience in the same locality, anticipated water impoundment, depth of overburden, intensity of weathering, abundance of fractures, strata composition, and coal cleat. As Wu (*11*) has emphasized, "... no one approach to the problem of designing or evaluating a barrier pillar can be considered universally applicable or correct."

The current method of estimating barrier widths came about largely as a result of experience with internal and property barriers. From a safety standpoint, it was considered important to leave a barrier to prevent impounded water from endangering the lives of persons working underground. The following described method evolved from the early 1900's and still is used to a varying degree by mining companies and regulatory agencies throughout the Appalachian coal region.

The State of Pennsylvania organized a seven-member commission to study the problem of barrier pillars between adjacent mines and to formulate recommendations for interior barrier widths. The formula derived by the commission was named after George H. Ashley, the State Geologist at that time and one of the commission members. After much discussion and deliberation the following formula was derived: $W = 20 + 4t + 0.1D$, where W is the width of barrier, t is the coalbed thickness, D is the thickness of overburden, or if water is involved, the height of the hydrostatic head possible if it is greater than the vertical thickness of the overburden. The width, W, was to be divided equally on both sides of a property line.

Thus, for a 4-ft-thick coalbed with 60 ft of overburden: $W = 20 + 16 + 0.1 \times 60$, or $W = 42$ ft.

A width of 42 ft for a barrier pillar would be somewhat less than half of the 100-ft width commonly used in drift mines based on experience and a rule of thumb that doubles the calculated width as a safety factor.

However, Ashley's method does not take into account many of the geologic conditions such as joint density and weathering, and structural discontinuities, which will affect the integrity of the barrier. These parameters are difficult to determine. Peters (*5*) stresses that, "... without the most serious study no definite conclusions can be drawn as to drainage paths through either old workings or strata, or the efficacy of barriers." It is clear that these parameters can be highly variable and overshadow the importance of simple engineering relations. For example, where a 100-ft-wide barrier usually assures a stable entry and adequate protection against water seepage, the presence of slickensides, fractures, or faults, can cause severe problems with roof failure and water leakage across a barrier. Unfortunately, current geotechnical methods do not always provide a ready means of predetermining pillar adequacy and thus overdesign of barrier widths may be the only safe option available.

A recent study, by Dames and Moore (*12*), was conducted to develop design criteria for barrier pillars that will minimize the seepage of impounded water. This study included computer modeled seepage analysis. Six histories of barrier failure as regards seepage were presented. Barrier widths in these examples of failure ranged from 15 to 400 ft. It was emphasized that further research is required to provide input as to the physical properties of coal measure strata in the barrier zone before critical values for design can be established.

Miller and Thompson (*13*) probed the various factors that influence the retardation of seepage by barriers in the Appalachian Plateau coal region and found that water usually flows along bedding and other separation planes such as joints and slickensides rather than through intergranular spaces. Pumping tests and pressure injection methods at numerous sites showed that the mean permeability of the overburden tends to decrease with depth, with the greatest permeability between a 50-ft depth and the surface. Any one area, however, will have its own individual hydrologic characteristics although extreme deviations from this general relation should be regarded as requiring verification.

EXISTING BARRIERS

The true width of an existing barrier can be determined only if both sides were subject to an accurate survey. If only the map of a long abandoned mine is used in planning there is great uncertainty about the accuracy of barrier width because of past mining practices.

Partly as an outcome of the Chasnala disaster, a method of test drilling has been established in India to investigate barriers and seepage or flow of impounded water. The method, described by Dutta (*14*), utilizes a lightweight electric drill with a noncoring bit, flow control valves, and anchoring bolts. The method provides a safe means of measuring coal barrier width up to 500 ft and tapping high-pressure impounded water. Similarly, Gulati and Singh (*15*) present a scheme of test drilling, using a pneumatic drill, to probe barriers of uncertain width in advance of entries. In situations where the limits of nearby flooded workings are known, but not the width of the existing barrier, Rogos (*16*) has devised a method for calculating the quantity of water being held in caved, sand-filled, gobbed, or open, shortwall and longwall systems. This provides a good estimate of the amount of water that must be handled on completion of test holes that penetrate a barrier.

Aside from test drilling there is presently no fully satisfactory method of determining barrier width and configuration from one side only, although geophysical methods such as ground penetrating radar are in a developmental stage and offer some promise of success in the near future.

GEOTECHNICAL CHARACTER OF BARRIERS

Generally, very little is known about the permeability, mechanical property, or detailed structure of the strata overlying or underlying a coal barrier. Wide variations can be expected in the vicinity of joints, faults, paleochannels, slickensides, or lamination of contrasting lithology. Coal appears to be more uniform in structure although permeability can range from 0.01 to 100 mD in undisturbed coal to much higher values in stressed pillars. It is self-evident that any information on the geotechnical character of a barrier zone will be of some help in either design of a barrier or assessment of an existing barrier. Such information is difficult to acquire but may become crucial in dealing with large impoundments of water.

When interviewed on underground water problems, several operators of mines in the northern Appalachian coal region reported that coal barrier widths of 200 ft proved adequate for impounding water with up to 300 ft of head. No serious leakage occurred and only small seepages through the coalbed and roof were reported. Ashley's formula indicates that a 200-ft barrier can impound up to 1,600 ft of water head. This information seems to suggest that serious leakage of barriers may not be a common problem because overdesign is commonly practiced.

Engineering guidelines for barrier design or assessment of a mechanically competent barrier do not necessarily assure that the barrier will be impermeable to leakage of impounded water, therefore an assessment of the hydrologic conditions in the vicinity of a barrier should go hand-in-hand with any layout that will determine the final configuration of a barrier. This is a task requiring the ability to recognize or anticipate local anomalous conditions in the geohydrology of the barrier zone. While rock permeability values obtained by core drilling may be useful in an overall evaluation of rock mass properties the increased permeability caused by local geologic structures often far outweighs these values by many magnitudes.

It is generally recognized, and supported by numerous observations, that while impounded water will gradually seep through a coal barrier in minor quantities the greatest leakage will occur along bedding planes just above or below the coalbed or along localized geologic structures such as faults, joints, paleochannels, and slickensides. Thus, in laying out barriers every possible precaution should be taken in order to avoid anomalous geologic conditions. Locating and identifying these conditions may be a formidable task but is should not only help avoid a sudden barrier failure and inrush of water but seepage will be held to an acceptable level and will not increase.

CASE STUDY OF BARRIER LEAKAGE

The case study that follows is intended to present the conditions that were encountered along an interior barrier subject to severe leakage. The geohydrologic conditions related to the leakage problem will be described, from which certain inferences can be drawn that might be helpful in avoiding barrier leakage at other sites. This study explains why a barrier of apparently more than adequate dimensions failed to prevent a substantial influx of water from an adjacent flooded mine.

GEOLOGIC SETTING

The subject mine is located about 12 miles southeast of Morgantown, WV (fig. 2), and operates in the Upper Freeport Coalbed (Allegheny Formation, Pennsylvanian System). The generalized stratigraphy of the mine overburden is shown in figure 3.

The depositional environment of the Allegheny Formation in northern West Virginia is nonmarine upper delta plain. The shales and coals were deposited in a floodplain lake and swamp environment. These fine-grained sediments sometimes were removed in places by scour and fill of the overlying sands as a prograding fluvial system extended over the lakes and swamps. The sandstones were deposited in fluvial systems, that is, by meandering, braided streams and rivers with marginal levee-cravasse, channel bar, and channel-fill accumulations. The coarse-grained sandstone occurring in some of the mine overburden suggests that a slow rate of reworking or winnowing has occurred in which the largest grains are no longer moved along by the river currents, but finer particles of sand, silt, and clay continue to be carried away even when currents are minimal. This situation could occur in the waning currents of a stagnating stream channel.

The coalbed is 48 to 54 in thick and dips about 2° westward towards the axis of the Ligonier Syncline (fig. 4). The principal coal cleat trends are N 10° E (butt) and N 79° W (face). Immediately beneath the coalbed is 2 ft of dark gray clay shale. The immediate mine roof normally consists of 2 to 15 ft of hard shale and shale with sandstone streaks. This is overlain by 50 to 60 ft of generally massive, coarse-grained Mahoning Sandstone. Roof rolls, or sandstone-filled paleochannels, sometime extend a short distance into the top of the coalbed. This quartzose sandstone is extremely hard and presents a severe problem when attempting to drill roof bolt holes. Slickensides in the roof are common but generally not troublesome when supporting roof. No well-developed system of jointing or faults has been detected in this mine. Overburden ranges from 0 ft at the portal to 225 ft near the western limits (fig. 5).

MINE DEVELOPMENT AND WATER PROBLEMS

The mine was opened in 1982 and developed westward, downdip, and adjacent to a flooded mine. Transverse (fig. 6) and longitudinal (fig. 7) profiles illustrate these relations. Large coal reserves lie west and downdip of the adjacent mine and access to these reserves, other than by shaft or closely skirting the adjacent mine, is limited.

In the area of closest proximity between the two mines the safety barrier was purported to be at least 450 ft wide; however, it was in this area that water was first encountered during development of the active mine. It entered the mine through roof bolt holes, with minor seepage through the coalbed. The water inflow was at first clear and pure, but gradually became acidic and discolored with iron oxides. An analysis of the water (table 3) clearly confirmed that it was acid mine drainage in contrast to ground water roof drippers from another wet portion of the mine (table 3). The adjacent flooded mine was the only likely source of such water in the vicinity, and this adjacent mine was flooded nearly to the portal, a depth of 140 ft, thus exerting a pressure of about 61 psi against the barrier.

This inflow immediately raised concern as to the adequacy of the barrier between the two mines as protection against a larger and more rapid inflow of water, or long-term persistent flow requiring pumping and treatment. Mine development continued for about 1,000 ft westward beyond the point of greatest inflow, which averaged 240 gpm. Roof drippers of the acid mine water persisted over most of this 1,000 ft and roof bolt holes also continued to discharge some water.

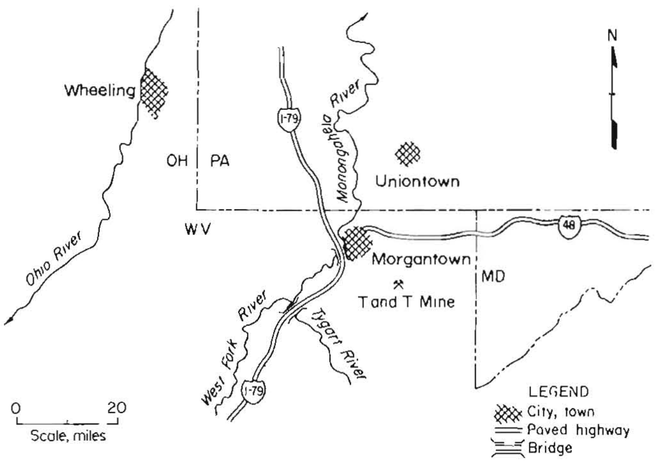

Figure 2.-Index map of study area.

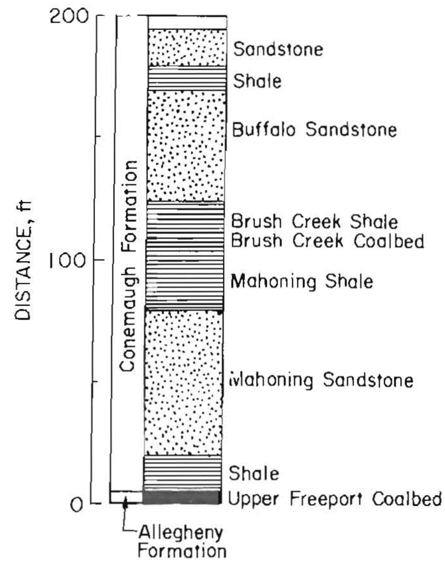

Figure 3.-Generalized stratigraphic column of mine overburden.

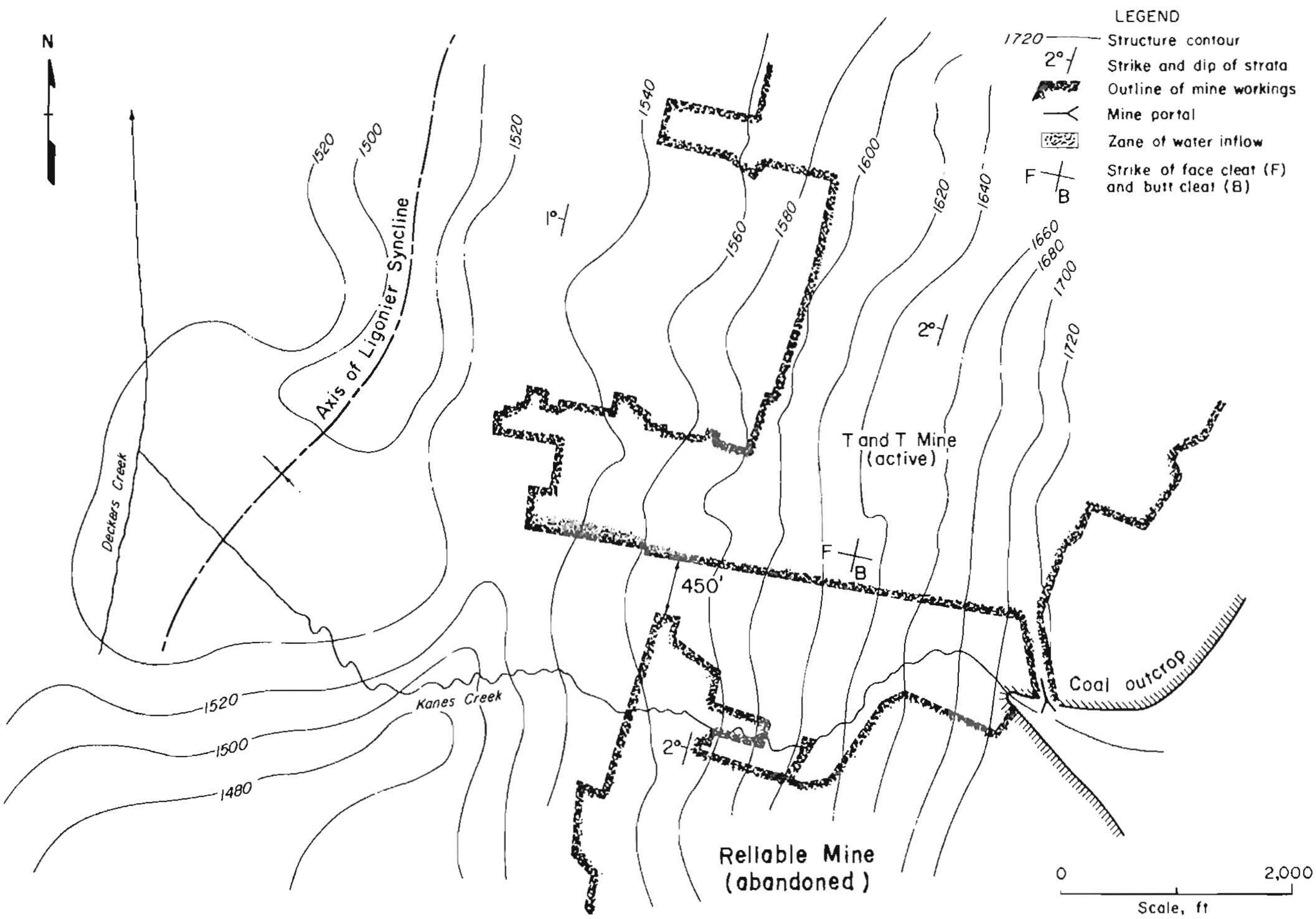

Figure 4.-Structure contours on Upper Freeport coalbed.

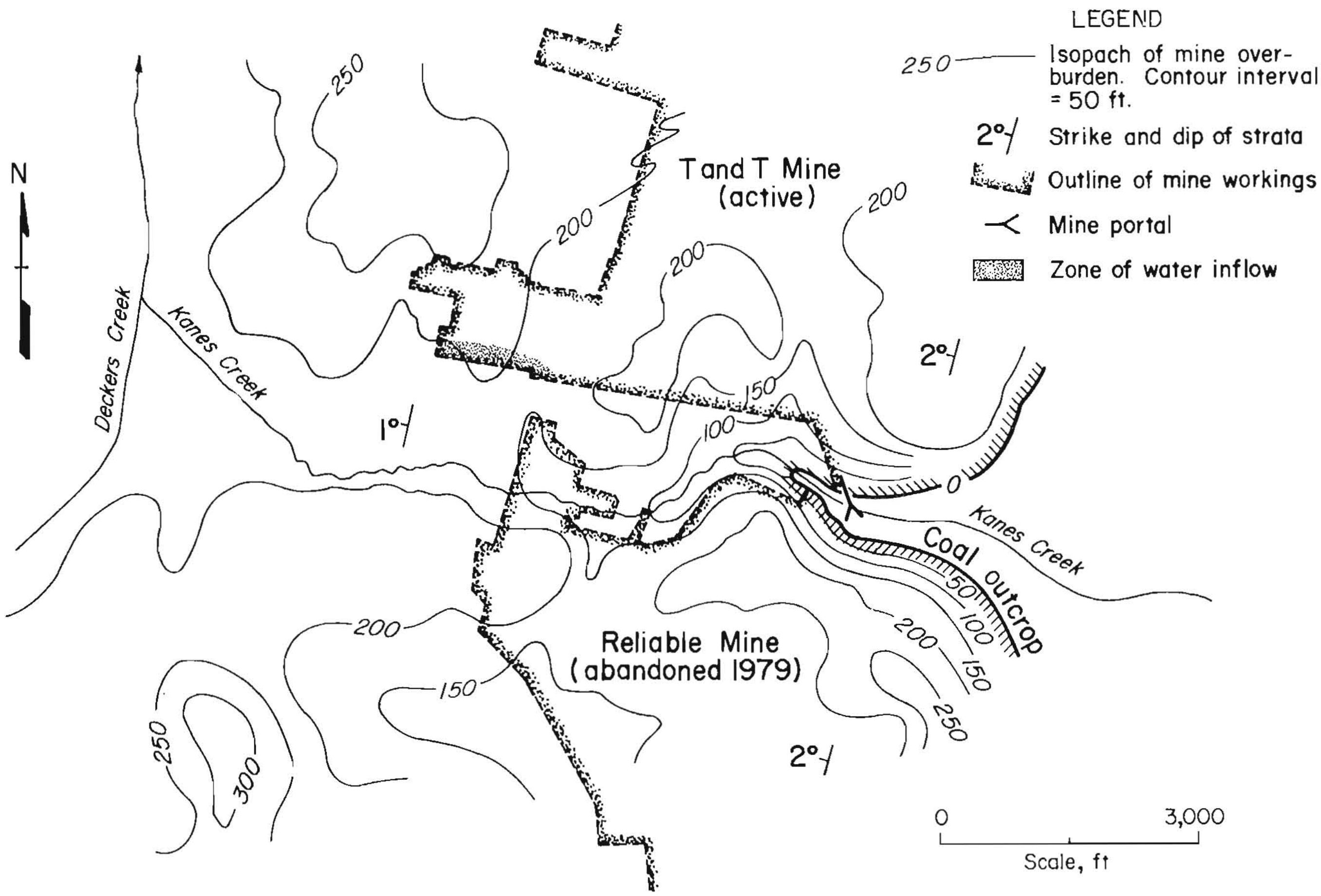

Figure 5.–Isopach of mine overburden.

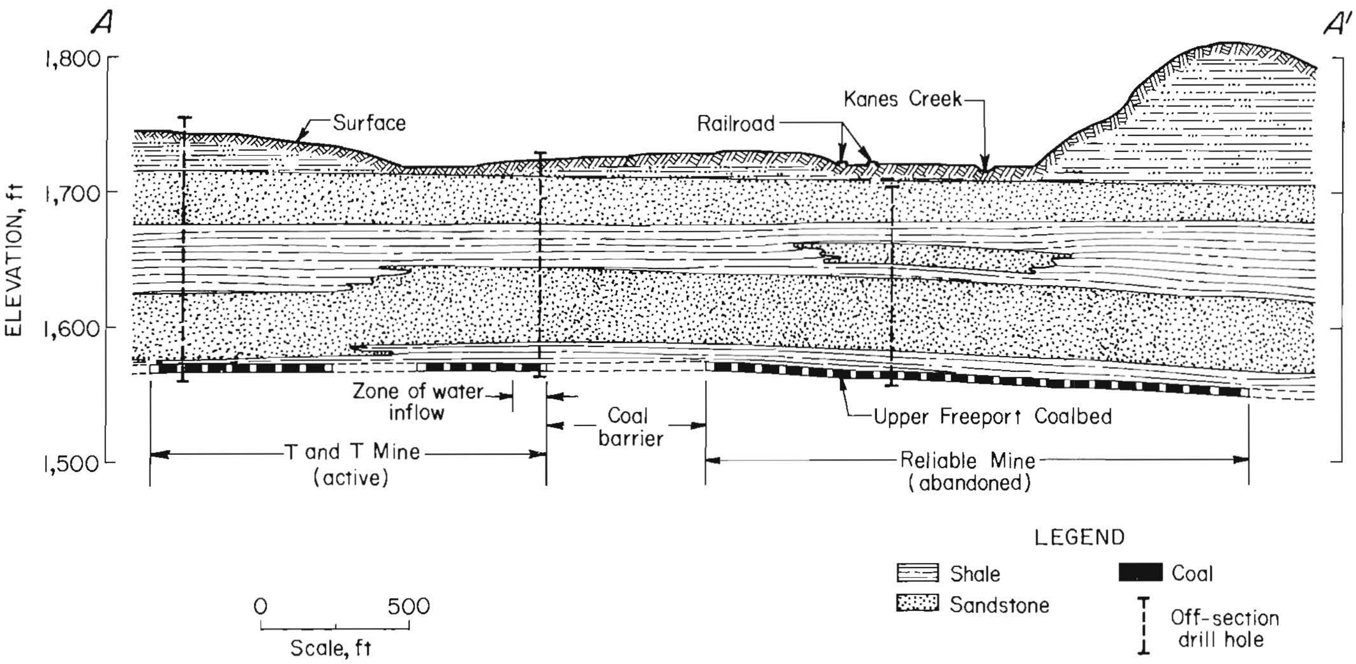

Figure 6.–Transverse profile of mine area.

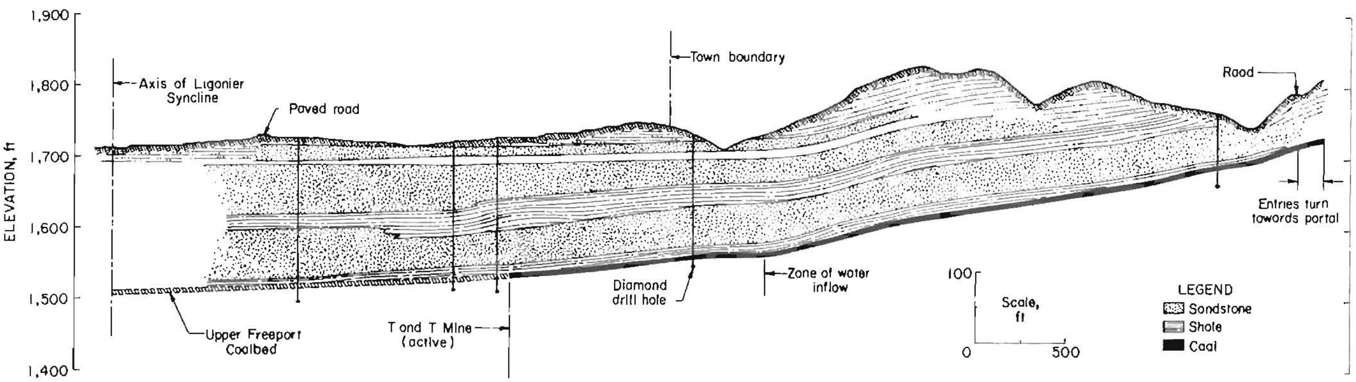

Figure 7.–Longitudinal profile of mine area.

Table 3.–Analysis of water from mine roof, parts per million

(pH: barrier leakage, 5.5; roof drippers, 7.3)

	Barrier leakage	Roof drippers, North Section
Alkalinity, as $CaCO_3$	15	241
Acidity, as $CaCO_3$	367	ND
Dissolved solids	1,916	338
Ferrous iron, as Fe^{++}	204	2
Total iron	1,206	2
Calcium, as Ca^{++}	271	118
Magnesium, as Mg^{++}	69	28
Sulphate, as SO_4^{--}	1,310	185
Manganese, as Mn^{++}	4	.2

ND Not detected.

Visual examination of roof falls near the point of major water inflow revealed a pronounced change from the normal hard shale roof throughout most of the mine to a locally soft deformed claystone with some lenses of hard sandstone. The identity and trend of the geologic structure in the roof could not be determined easily because of the ragged and iron-stained condition of the roof (fig. 8). Some discernable fracture trends are shown on figure 9.

Because of the wide spacing of surface drill hole data points neither isopach (fig. 10) nor structure contour (fig. 4) maps suggested any local conditions that might account for the water. The existence of a surface diamond drill hole that passed within 100 ft of the major leakage was of little help in explaining the anomalous conditions because the driller's log was generalized and showed only a normal stratigraphic sequence and a very thick section of undifferentiated sandstone.

WATER HANDLING COSTS

Prior to the leakage of mine water across the coal barrier, the water collected from other sections of the active mine required little treatment. However, as the flow of water across the barrier increased in quantity and deteriorated in quality, a much heavier burden was placed on the existing treatment plant and additional pumping capacity was required.

The existing water treatment plant was constructed at a cost of $250,000, and two large settling ponds were excavated at a cost of $150,000. The annual consumption of hydrated lime currently averages 150 tons, at a cost of $11,000. Annual power supply for the plant is an estimated $2,000. The settling ponds must be dredged occasionally and other maintenance must be performed on a regular basis adding to the overhead cost.

The additional inflow of water from across the barrier necessitated a new 1,000-gpm-capacity pump costing $80,000, 5,000 ft of pipe at $30,000, and power consumption cost increase to $6,000 per year. It is evident from these costs that any increase in water, especially of poor quality, constitutes a heavy continuing cost burden on an operating mine and any feasible means of avoiding or abating this problem is worth serious investigation.

CORE DRILLING

Because of the sparsity of needed information to assess the barrier leakage and accompanying roof deterioration in the vicinity it was concluded that core drilling was essential before any further development in that section of the mine was attempted. Information from core drilling might provide some insight into the geologic structure near the barrier zone, the effects of such structure on barrier integrity, and the width of the water-bearing zone or pathway–all major factors in barrier assessment. No attempt was made to drill through the entire 450 ft or more of coal barrier and into the impounded water because of time constraints, possible drill hole deflection into roof or bottom rock, and the hazards of needlessly trying to install a borehole packer against high pressures.

Precautions

All underground core drilling was conducted in fresh air intake entries and checks for methane were conducted periodically. The roof was scaled at each drilling site and the hydraulic props used for supporting the drill provided additional support for the roof in the immediate vicinity of the drill. Both mechanical and inflatable 3-in packers were available at each site to close off any holes that might have intercepted a large flow of water.

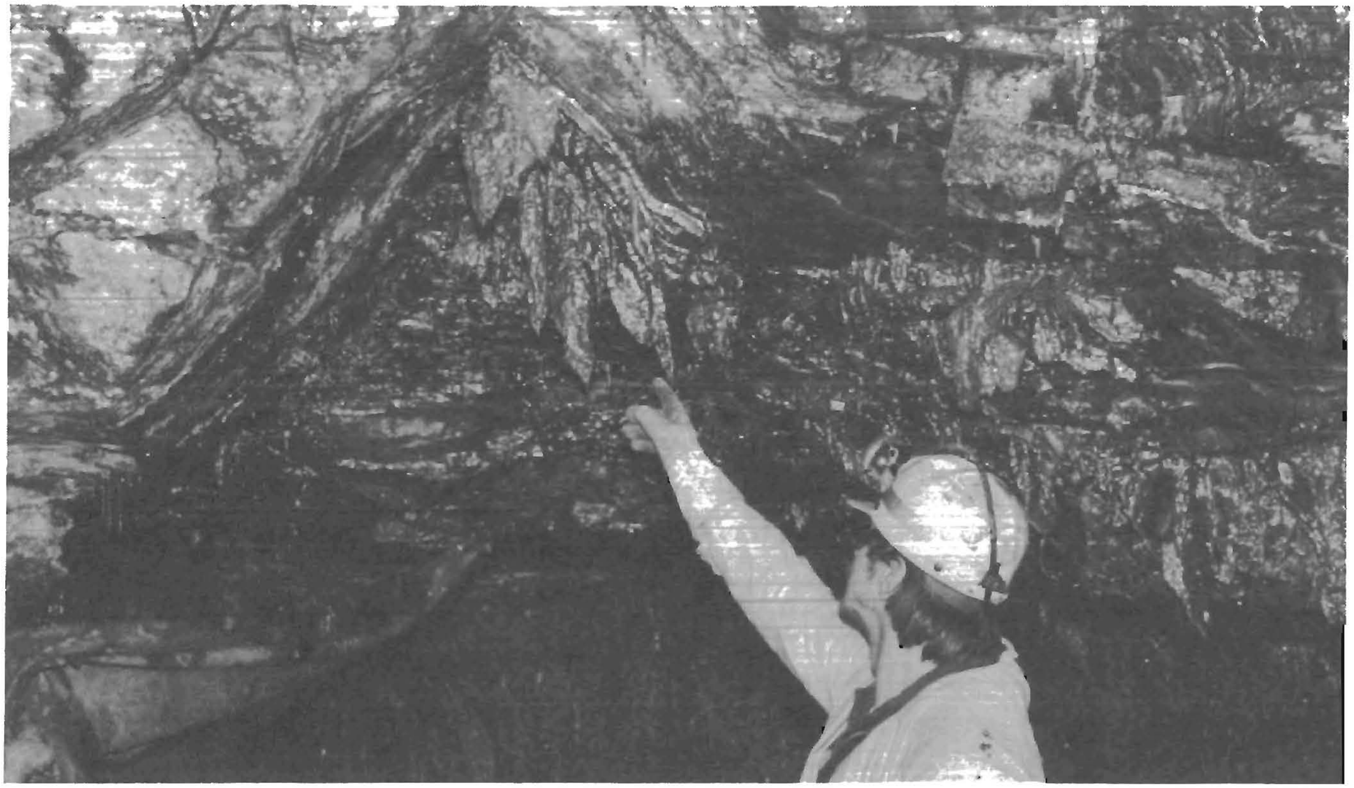

Figure 8.-Ragged character of mine roof and deposits of yellow boy.

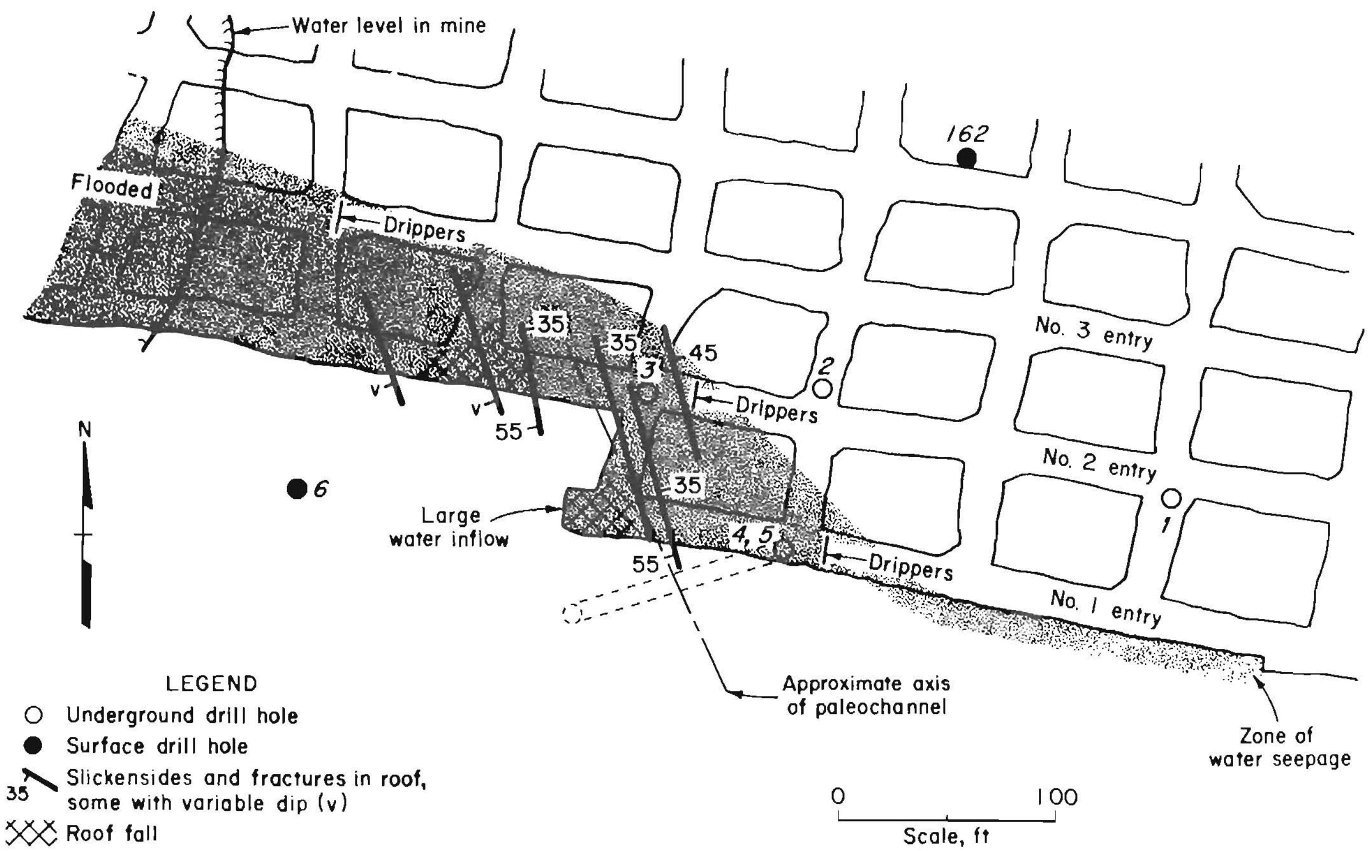

Figure 9.-Fracture trends in zone of large water inflow.

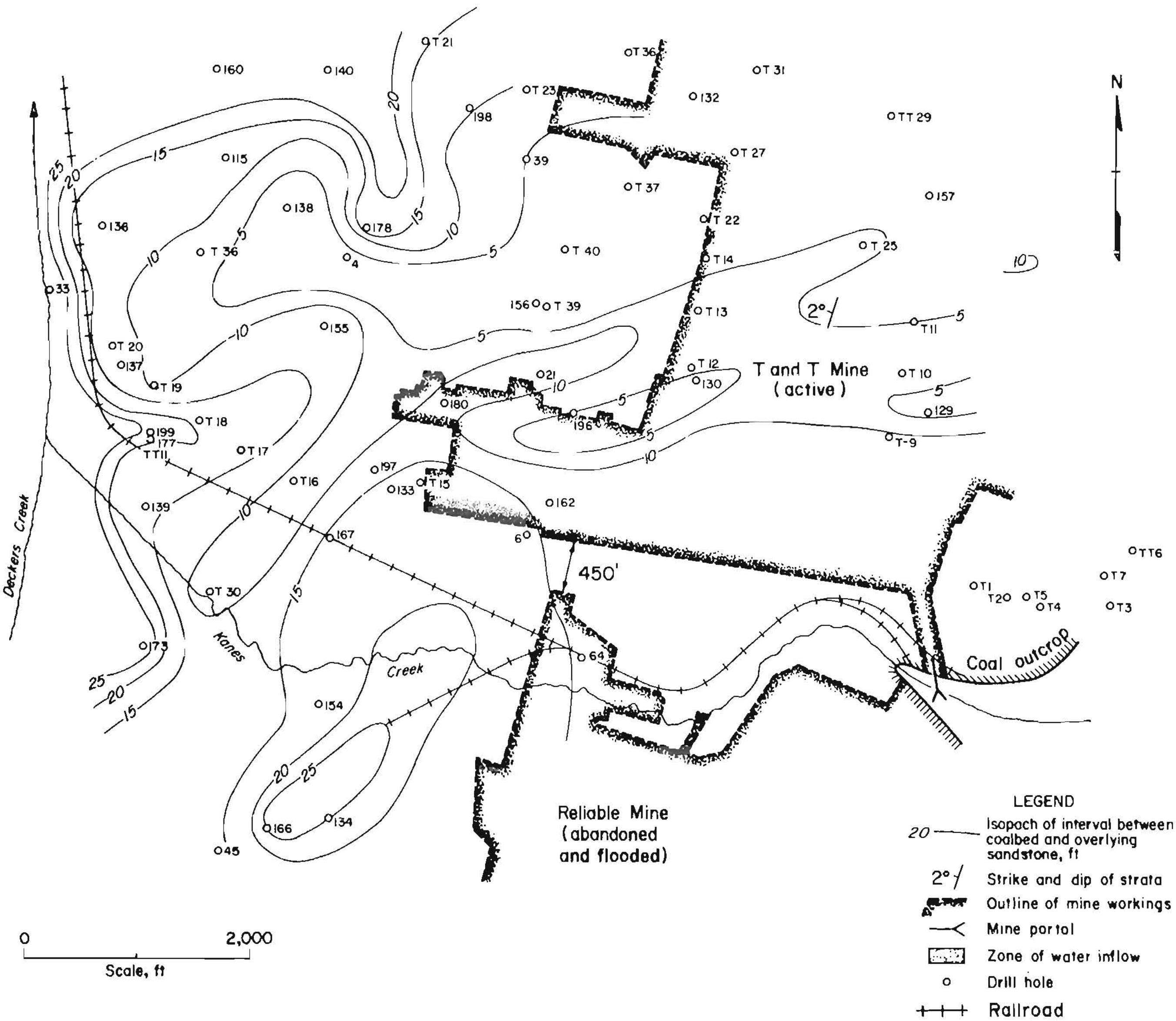

Figure 10.-Isopach of interval between coalbed and overlying sandstone.

Equipment

The equipment used underground for core drilling the mine roof included a Victor Minotaur hydraulic drill,[4] a 15-hp, 440-V ac electrohydraulic power pack, and accessories needed to obtain 2.1-in-diameter core. A standard mobile truck mounted rig was used for drilling the surface borehole.

Location of Drill Holes

Five underground holes (Nos. 1-5) and one surface test hole (No. 6) were completed in the course of work at the mine to assess the barrier leakage. Surface hole 162, in the vicinity of these holes, had been drilled many years earlier. Drill hole locations are shown on figure 11.

Three vertical holes (Nos. 1-3) were drilled into the mine roof in No. 2 entry, hole 4 was drilled into the roof of the No. 1 entry at +8° and angled 30° left off the entry to probe for a possible northwest-trending fracture zone that might be related to the barrier leakage. Hole 5 was collared in the coalbed just below hole 4 and was drilled horizontally in an attempt to measure coal permeability and formation pressure.

Hole 6, drilled from the surface, was intended to help define rock structure in the vicinity of the other holes and as a means of sampling water.

[4]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

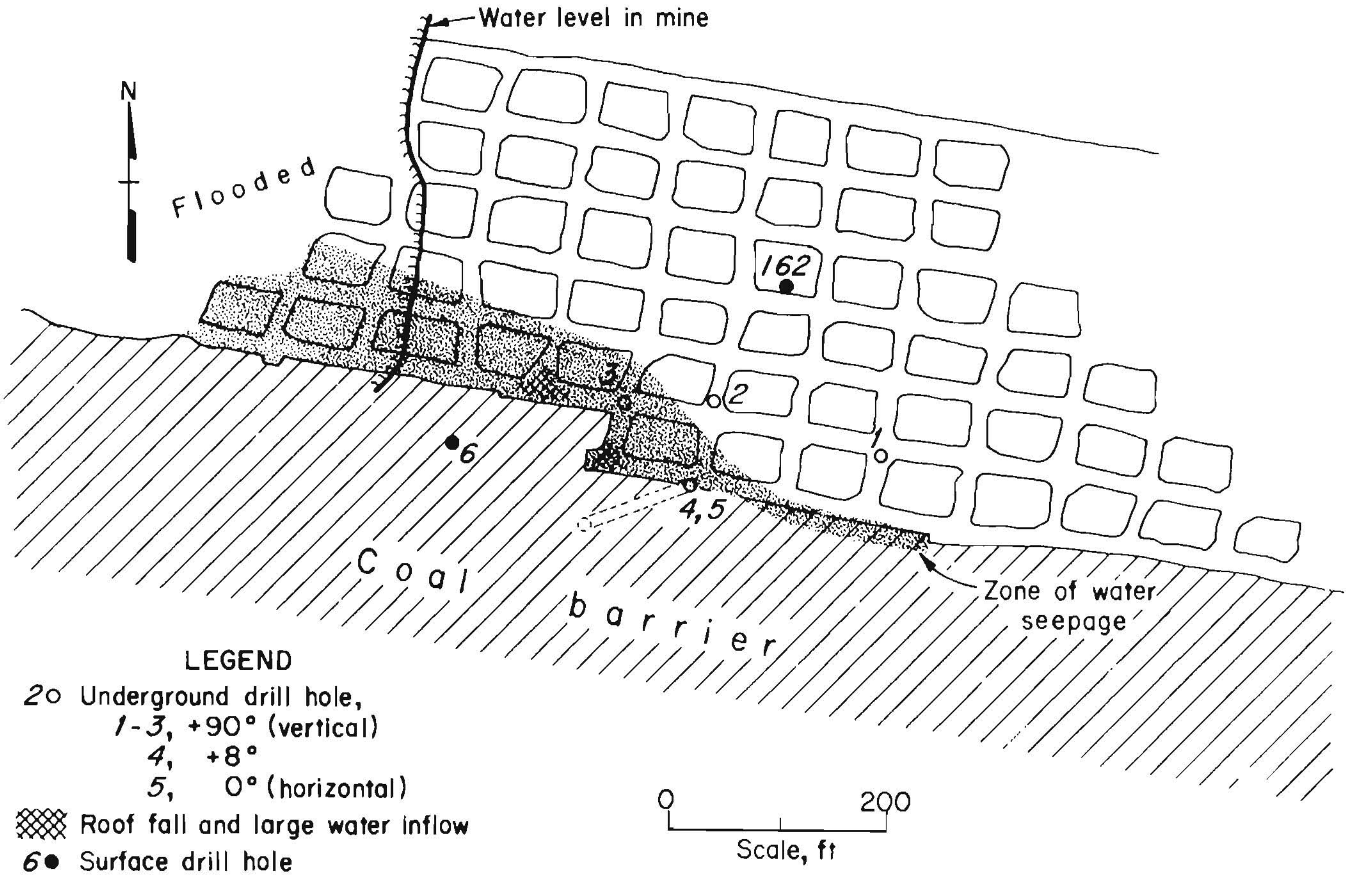

Figure 11.–Location of drill holes and zone of water seepage.

RESULTS OF CORE DRILLING

The results of drilling the first three holes are illustrated in figure 12. Where core descriptions are followed by a three-digit number in parentheses the number refers to Ferm's classification (*17*) of cored rock. A channel-like structure in the roof was inferred from the sandstone configuration although sandstone channel-fill commonly represents lateral accretion, vertical accretion, or both, and is not necessarily a measure of channel shape. The lower part of the channel consists of a medium-grained, light gray, quartzitic sandstone with occasional shale streaks, while the upper part is a massive, coarse-grained, almost conglomeritic, poorly cemented sandstone. Coarse-grained sandstones commonly characterize channel deposits of the upper delta plain and alluvial plain environments.

The two contrasting phases of sandstone perhaps are best illustrated in figures 13 and 14, which show the rock cores and corresponding thin section of each type. A comparison of the thin sections reveals the following contrasts in the characters of the sandstones:

Medium-grained quartzitic sandstone.–Highly compacted and cemented sand grains, chiefly silica matrix with some sericite.

Coarse-grained sandstone.–Poorly compacted and cemented sand grains; abundant sericite and clay matrix with some silica.

The base of the sandstone channel at hole 3 lies about 3 ft above the mine roof and has little effect on the roof stability, although about 50 ft west of hole 3 near the margin of the channel the roof conditions are poor, supplementary support is required, and roof drippers are profuse. This difference could be attributed to the effects of differential compaction, with the formation of distorted bedding, slumping, and slickensides, commonly associated with the margins of sandstone-filled channels.

Virtually no water inflow was intercepted in either holes 1, 2, or 3. This indicates that the local water pathways lie at least 50 ft westward where the roof drippers occur. It also indicates that the sandstone channel-fill itself does not constitute an aquifer or significant pathway for the water impounded in the adjacent mine. Roof and water conditions precluded the drilling of a test hole west of hole 3 where some marginal effects of the channel, such as slumping and slickenside concentrations and enhanced permeability, might have been detected.

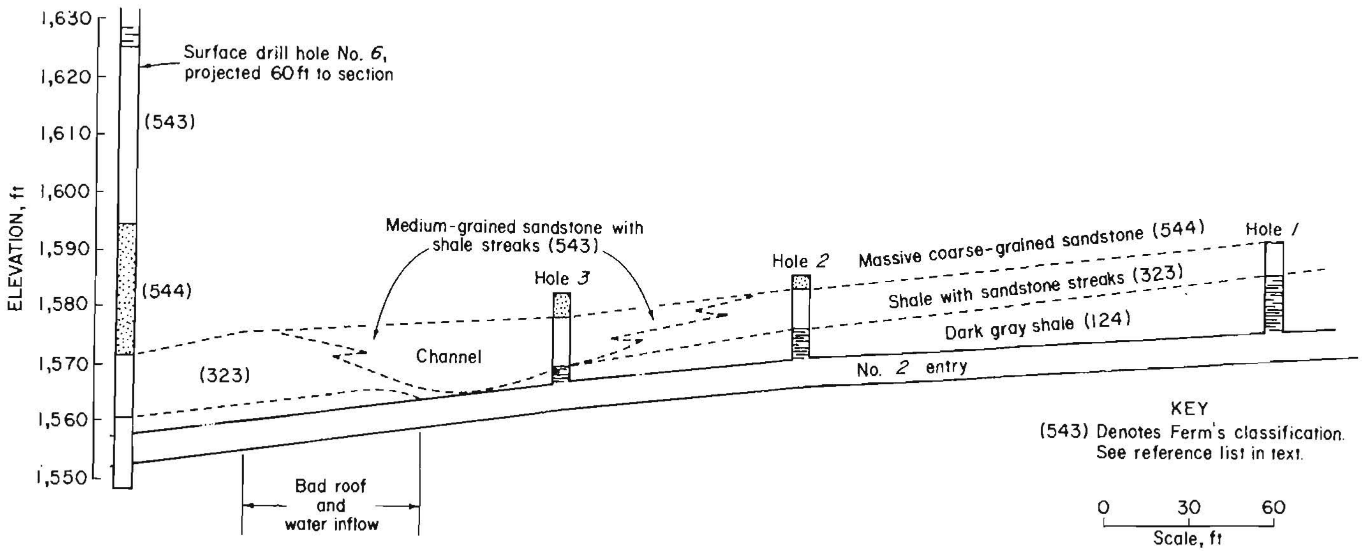

Figure 12.–Profile of mine roof showing structure and lithology based on core drilling.

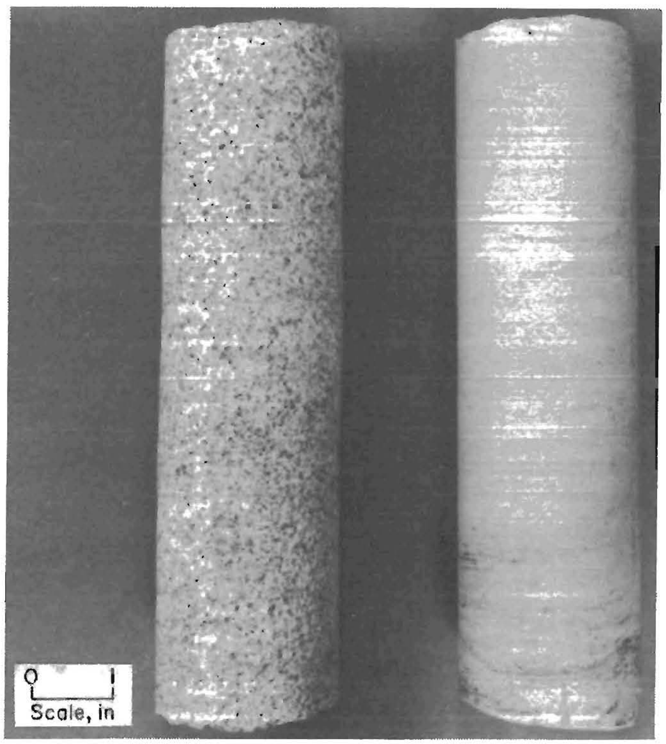

Figure 13.–Medium-grained channel-fill sandstone (right) and overlying coarse-grained Mahoning Sandstone (left).

Figures 15 and 16 summarize the results of drilling hole 4. This hole was drilled to probe a northwest-trending zone of possible bad roof and water pathways as postulated from information provided by the mine personnel and based on observations prior to the flooding of the west end of the mine. This hole had a discharge volume of about 3 gpm on completion, all from the first 15 ft of the hole and therefore within 3 ft of the top of the coalbed. This suggests lateral flow along roof rock bedding planes, rather than through the overlying sandstones. Hole 4 also penetrated the same channel-fill sandstone encountered in holes 1 and 2, although from this perspective the exact shape of the channel can be interpreted in more than one manner. The exact trend of this channel could not be determined from the information provided by this hole. The shut-in pressure for hole 4 stabilized at 2 psi, after which leakage from the roof nearby the drill hole increased noticeably.

Hole 5, drilled horizontally into the coal barrier (fig. 11) to a depth of 50 ft produced only 0.75 gpm on completion. This, along with the very gradual seepage of mine water from the solid coal rib into which the hole was drilled, strongly indicates that the coalbed is a poor aquifer and not the pathway for the large quantities of water flowing from the mine roof.

Hole 6 was drilled from the surface to the base of the coalbed at a depth of 208 ft. It was located 125 ft ahead of the No. 1 entry (fig. 11) to help define the margin of the sandstone channel inferred from the logs of holes 1 through 5, and provide for sampling ground water. The water level in the hole stabilized at 88 ft below the surface or 108 ft above the coalbed.

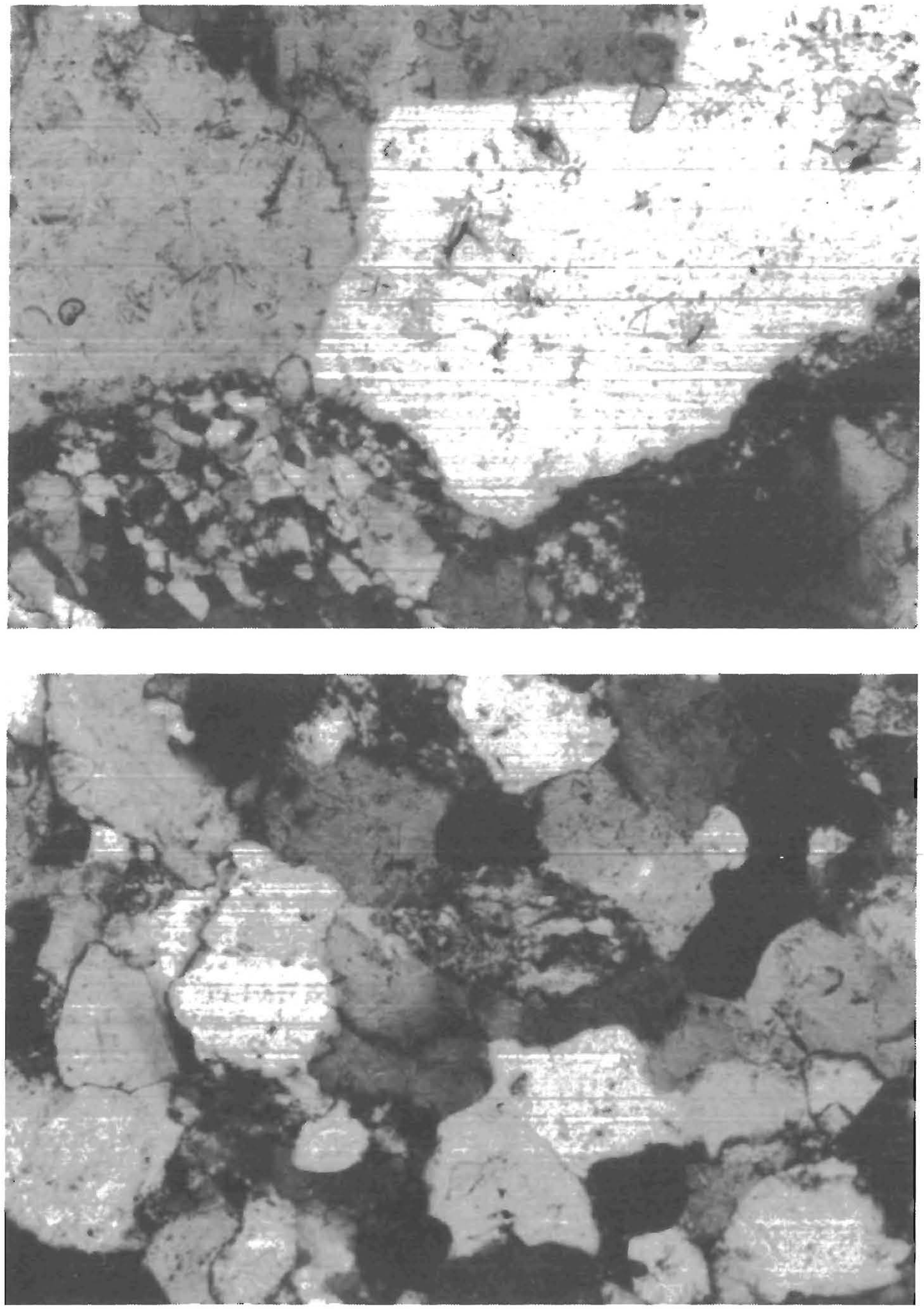

Figure 14.–Texture of channel-fill sandstone (bottom) and overlying Mahoning Sandstone (top) (× 100).

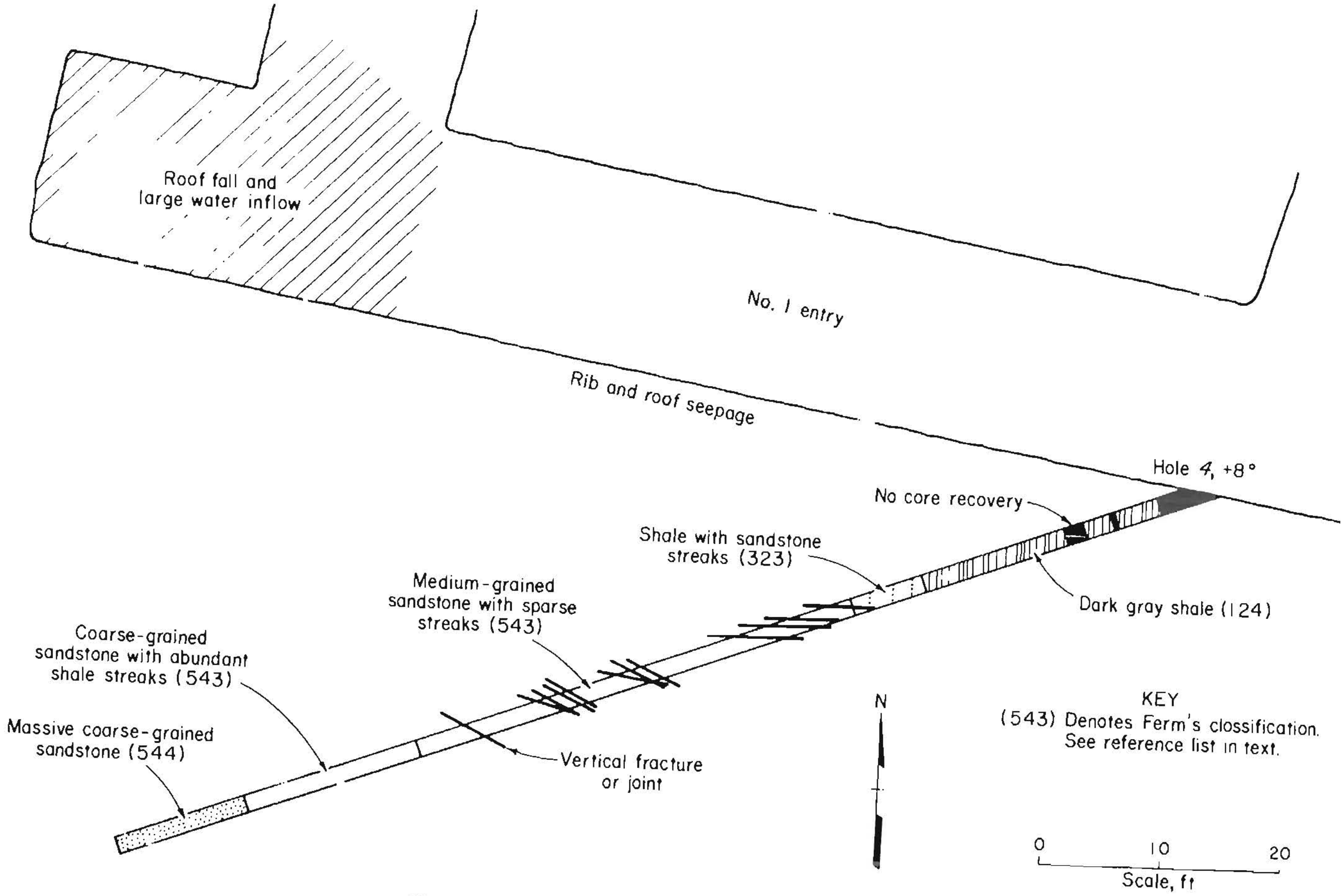

Figure 15.-Plan view of drill hole 4 and No. 1 entry.

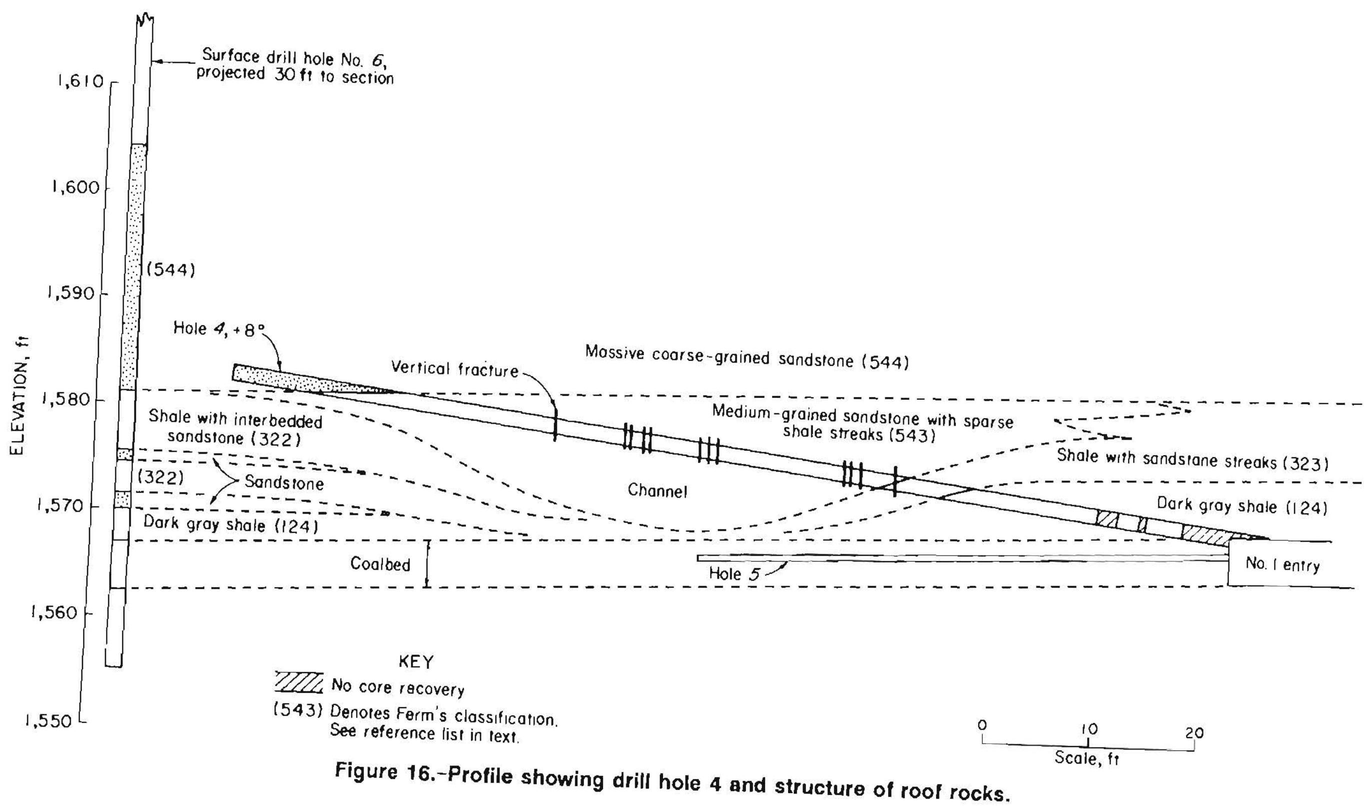

Figure 16.-Profile showing drill hole 4 and structure of roof rocks.

DISCUSSION OF RESULTS

In view of the general effectiveness of 200-ft-wide coal barriers in impounding water, as discussed previously, the situation at the study site requires some unusual conditions to explain the leakage such as–

1. Anomalous geologic structure to provide a high permeability pathway for water to flow across the barrier.

2. A laterally extensive aquifer close to the top of the coalbed.

3. A gross error in the map location of the adjacent mine workings or an unrecorded extension of the workings resulting in a greatly reduced barrier width.

A fourth and somewhat remote and conjectural condition that might explain the unusual leakage may result from valley floor rebound and related effects. This effect has been widely observed in the northern Appalachian coal region and elsewhere (*18-23*). While this site of leakage lies nearly 2,000 ft from the nearby Kanes Creek it lies beneath the valley of a small tributary with 100 ft of topographic relief. This situation seems an unlikely explanation for the barrier leakage unless bedding plane separations have occurred only near the top of the coalbed and the seepage was facilitated by the 61-psi hydrostatic pressure in the bottom of the adjacent mine. Enhanced permeability in the vicinity of stream valleys is occasionally reported by coal mine operators but usually where topographic relief is greater than at the study site. Nonetheless, while valley-related effects are poorly understood they always should be suspected in dealing with the ground control or water problems of shallow (less than 400 ft) mines.

The underground and surface drill hole information developed during this investigation indicates no major geologic discontinuities such as faults in the vicinity of the barrier leakage, although zones of slickensides in the mine roof were observed at roof falls in the zone of leakage. A sandstone-filled paleochannel in the mine roof was inferred from drill hole information and the trend of the channel generally was in the direction of the adjacent flooded mine. However, no evidence was acquired that could confirm the continuity of the channel across the entire width of the barrier nor could it be shown conclusively that the channel and marginal slickensides acted as a discrete pathway for water to follow directly from the adjacent mine. The laterally extensive presence of water in the mine roof on the side toward the adjacent mine suggests a mechanism more pervasive than that generally attributed to a narrow, linear paleochannel structure.

Former operators of the flooded adjacent mine reported that in the north entries close to the current barrier the roof was "not good," the entries were damp, and roof drippers were common. Dampness often occurs because of high humidity and condensation, especially during the summer season. Roof drippers, however, are suggestive of an increased permeability to ground water, often where abundant slickensides occur near the margins of clay veins or paleochannels in the mine roof. The slickensides tend to act as pathways along which ground water can readily migrate.

The sparsity of documented experience with the geohydrology of barrier leakage problems in U.S. bituminous coal mines was a handicap in attempting to interpret the results of this study. Many examples of sudden inrushes have been published because of the resulting fatalities, however, barrier leakage seldom is deemed noteworthy of publication. As most mine operators can attest, water, even in small quantities is a nuisance, and it may be indicative of severe water problems if flooded workings are in the vicinity.

CONCLUSIONS

While the results of this investigation were not conclusive with respect to delineating precisely the manner in which the water flows from a flooded mine, across a minimum 450-ft-wide barrier, and into an active mine at an average rate of 240 gpm, some general conclusions can be offered as follows:

1. The paleochannel detected in the mine roof probably served to facilitate the flow of water from the abandoned mine to the active mine.

2. Water, on reaching the vicinity of the active mine, spreads out laterally in a zone confined to 0 to 5 ft above the top of the coalbed.

3. The quality of the barrier leakage is fairly typical of acid mine water, further evidence that the source of the water is the adjacent mine. This water inflow is largely on the side of the active mine facing the adjacent flooded mine; a further indication of the source.

4. Leakage through the coalbed is very gradual and by itself does not constitute a problem to the mine operation, but does serve as an indication of a nearby source.

5. In the absence of anomalous geologic conditions an interior coal barrier 200 ft in width generally is adequate for impounding water with a hydrostatic head of up to 300 ft without serious leakage.

RECOMMENDATIONS

To assure safety during operations and to prevent water problems in future mining, barriers should be designed on conservative engineering guidelines with an added safety factor based on anticipated hydrologic conditions. A careful analysis of barrier zones should be conducted in an effort to detect the presence of any geologic conditions that might lead to barrier leakage or failure.

Typically, in coal mining little detail is known about geologic structures in the roof or coal prior to exposure. Most structures, unless sizable, escape detection by the customary surface boreholes, although on occasion these structures can be inferred by acute geologic analysis. Some of the more common structures in mine roof that might facilitate the flow of water around or through a barrier include faults, joints, slickensides, paleochannels, slumps, and lenses of high permeability strata.

Despite sound engineering and a large safety factor in barrier design, serious leakage can develop as a result of unforseen conditions such as those at the study site. Once encountered, serious water inflows can be managed in several different manners depending on the particular site conditions, as follows:

1. Handling excess water by ditching into a sump for pumping to the surface is the most commonly practiced method in Appalachian coal mines and is in line with underground operating procedures. Some diversion dams or gathering pumps may be needed if the water influx is widespread.

2. Intercepting water with boreholes in the roof and rib at regular intervals offers an advantage of confining the water to a piping system, keeping entries dry, and movement directly to a pumping site. This method is best when the water pathways are well-delineated and not widely pervasive throughout the workings.

3. Pressure grouting to block water inflow has been in use for decades. Here, again, a discrete grouting target is advantageous, as widely pervasive water inflow will entail a very costly effort and may simply block the inflow in one area forcing the water to seek other pathways into the mine workings.

4. Dewatering of an adjacent flooded mine, where feasible, may reduce the potential hazard of a sudden inrush or the cost of handling leakage. For example, the mine adjacent to the study site contains approximately 170 million gallons of water. This mine could be dewatered using a surface borehole and submersible pump in about 118 days at a continuous pumping rate of 1,000 gpm. This, however, does not allow for natural recharge in the abandoned mine. Treatment costs and sludge disposal are an added consideration.

5. In special circumstances, such as at mines where high acidity or other serious water-related problems are present, the aquifer dewatering approach as described by Fink (*24*) may be worth serious consideration. This approach requires detailed technical and accounting information for a particular mine. In a mine where ground water movement is chiefly fracture-dominated the effectiveness of induced drainage is extremely difficult to predict.

6. Above all other considerations is the safety of mine personnel. A monitoring system that detects changes in water levels or flow rates can be useful in providing an early warning of water hazard to miners working underground. In addition, a detailed evaluation of the potential flow patterns in the event of a sudden inrush should indicate the impact of the inrush on emergency escape routes and the ventilation.

Any water inflow in the vicinity of abandoned mines–whatever the water quality and whatever the indicated barrier width–is a danger signal. Statutory provisions of Title 30–Mineral Resources of the Code of Federal Regulations mandate drilling of boreholes of at least 20 ft in depth in advance of a working face and also in the rib, whenever within 200 ft of an abandoned mine that cannot be inspected. Unfortunately, it is not easy to verify the 200-ft barrier width. Mine maps, especially old ones, may be inaccurate and not fully up to date.

The information acquired from this study should be useful in indicating some of the uncertainties that should be considered in designing barriers to prevent inundation and in assessing existing barriers. The engineering methodology for designing barriers, while adequate under ideal or uniform conditions, is subject to the erratic and unpredictable occurrences of geologic discontinuities of various types. For assessing the adequacy of existing barriers, a thorough geotechnical investigation is essential.

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[5]A title enclosed in parentheses is a translation from the language in which the work was published.